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STOCHASTIC AND ADAPTIVE SYSTEMS.(U)
APR 78 M ATHANS, S K MITTER AFOSR-77-3281
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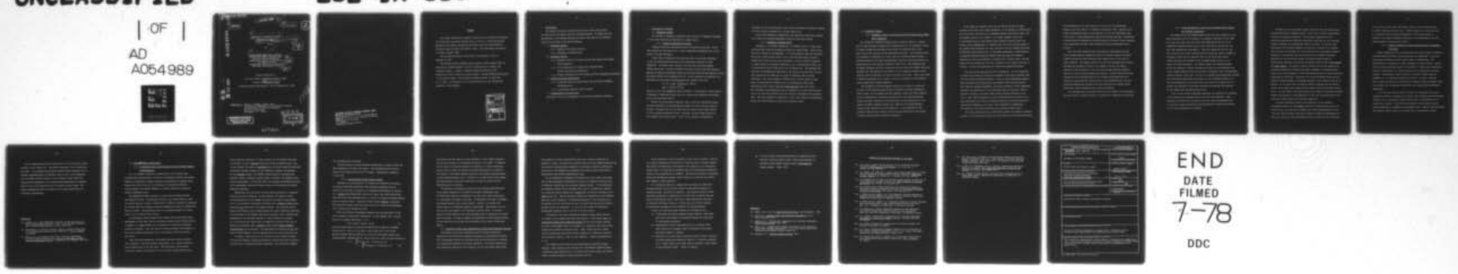

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(11) April 1978

(14) ESL-IR-815

(6) STOCHASTIC AND ADAPTIVE SYSTEMS.

(9) INTERIM REPORT, 1 Mar 77-28 Feb 78,

(12) 22p.

by

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(16) 2304

(17) A1

Research Supported by

Air Force Office of Scientific Research (AFSC)

Research Grant (15) AFOSR-77-3281

Covering the Time Period (March 1, 1977 to February 28, 1978)

Submitted to: Charles L. Nefzger, Captain, USAF
Directorate of Mathematical and Information Sciences
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SUMMARY

This report describes the research carried out by the faculty and students of the Decision and Control Sciences Group of the M.I.T. Electronic Systems Laboratory with support provided by the United States Air Force Office of Scientific Research under grant AFOSR 77-3281. The grant monitor was Charles L. Nefzger, Captain, USAF.

The time period covered in this report is from March 1, 1977 to February 28, 1978.

The following faculty members received partial salary support under the above grant: Professor Sanjoy K. Mitter, Professor Alan S. Willsky, and Professor Timothy L. Johnson. Professor Athans participated in the research but did not receive any salary support. Several students participated in the research effort. The research assistants were Mr. M. Bello and Mr. S. Jones. In addition, Mr. D. Ocone participated in the research but required no salary support.

1. Introduction

The research activities carried out during the current grant period are described in the sequel under the following headings. We remark that the descriptions of the research projects are brief, since many of the technical details can be found in the cited references.

1.1 Stochastic Systems

1.1.1 Studies in Non-Linear Filtering

1.1.2 Estimation in Random Fields

1.2 Stochastic Control

1.2.1 Stochastic Control of Linear Discrete Time Systems with Random White Parameters

1.2.2 On the Robustness of Constant Gain Extended Kalman Filters and Stochastic Regulators

1.2.3 Singular Stochastic Control Problems and Dual Compensator Structures

1.3 Reliabile Control System Design

1.3.1 On Reliable Control System Designs with and without Feedback Reconfigurations

1.3.2 Fault-Tolerant Optimal Control Systems

1.4 Implementation of Control Laws

Stochastic control laws implemented by finite-state sequential machines.

2. Description of Research

2.1 STOCHASTIC SYSTEMS

Our research on stochastic systems has been focused on fundamental problems of non-linear filtering and estimation in random fields.

2.1.1 Studies in Non-Linear Filtering

Professor Mitter has continued his work in non-linear filtering. He has been assisted in this work by Mr. D. Ocone (Mathematics Department) who is the holder of an NSF fellowship.

A great deal of theoretical work has been done on non-linear filtering in the last fifteen years and many of the theoretical questions are well understood. In another sense, however, the non-linear filtering problem remains quite open. Very few realizable non-linear filters have been obtained, progress of obtaining performance bounds has not been great and the stability of the non-linear filters is not understood at all. In this research our objective is to understand the non-linear filtering problem for systems of the form

$$d\,x\,(t) = Fx(t) + \sum_{i=1}^{N} G_i dw_i(t) + Hdv(t)$$

$$dy(t) = Jx(t)dt + d\,\xi(t)$$

where W_i V and ξ are independent Wiener processes. We have made a certain amount of progress in designing filters which will aymptotically approach the performance of the non-linear filter.

Firstly, the innovations conjecture, that is that the innovations contain the same information as the observations, appear to be true for this class of systems. We remark that we have found that the proof of some recent results on the innovations problem are false. Secondly, the best linear filter for this problem can be easily found. We are in the process of developing a procedure for the best polynomial filter which is obtained by solving a sequence of linear filtering problems for x and the powers of x.

We are also developing a generalized rate distortion theory which promise to be useful in obtaining performance bounds for non-linear filters.

2.1.2 Estimation of Random Fields

Professor A. S. Willsky, Professor N. R. Sandell, and Mr. M. Bello have continued their study of estimation problems for random fields. Earlier work had led to results on the estimation of a time-invariant field given measurements from a sensor which traced a line in one direction along the field. Clearly this initial work is very preliminary, as one is usually interested in random fields in two spatial dimensions (e.g., a gravitational field) and in sensor-motion along a path other than a straight line. The problems that arise are the probabilistic modelling of the field and the fact that the process observed by the sensor may no longer be Markovian when we change directions. As a first attempt to consider some of these issues, we have begun to investigate the estimation of a one-dimensional field given observations from a sensor that moves back and forth across the field. This introduces non-Markovianity into the problem, but we feel that the structure of the solution should be such that efficient algorithms would be developed. When this problems is understood, we will then consider two-dimensional fields and sensors which can travel along polygonal paths.

2.2 STOCHASTIC CONTROL

2.2.1 Stochastic Control of Linear Discrete Time Systems with Random White Parameters

Mr. Richard Ku, Professor Michael Athans, Professor Timothy L. Johnson, and Dr. David Castanon continued their investigations on the stochastic control of linear systems whose parameters are modelled as discrete white noise, both in the state equation and the measurement equations. This research effort was initiated to understand at a basic level the interrelationship between modelling errors in the state and measurement equations, and the existence and characteristics of the optimal stochastic control law. The assumption that the model parameters are white, quantified by their mean and standard deviations, precludes any dual effects in the solution of the stochastic optimal control problem, since by definition one cannot estimate white noise. Thus, this method of modelling represents, in a sense, a worst case behavior in the stochastic control problem with random parameters.

The assumption of white parameters allows one to obtain an analytical solution to the problem through the use of stochastic dynamic programming. Several cases of the problem have been examined, using first order dynamics so as to understand at the simplest possible level the interrelationship between the model uncertainty and the existence and characteristics of the optimal stochastic feedback control law. Research on the multivariable version of the problem is only now beginning. In the remainder of this progress report we shall briefly outline the characteristics of the optimal stochastic solution under different assumptions.

If one makes the assumption that one can measure exactly the state variables of the model with random parameters, in the presence of additive process white noise, and the use of a standard quadratic performance index, then the optimal solution (if it exists) is a linear feedback control law. In contradistinction to the standard Linear Quadratic-Gaussian case, the optimal linear feedback gain is a function not only of the average values of the random model parameters, but also a function of their standard deviations and possible cross-correlations. If the model uncertainty, as quantified by an algebraic threshold function dependent upon the means and standard deviations of the white parameters, increases over a certain value, then the optimal control problem does not have a solution as the terminal time goes to infinity. We call this phenomenon the Uncertainty Threshold Principle.

The next problem examined was that of estimation. In this formulation we examine the problem of obtaining an estimate of the state variables, when the state cannot be observed exactly. We use a linear measurement equation, which contained both multiplicative and additive white noise parameters. Even under the Gaussian assumption, one cannot calculate a finite dimensional estimator that generates the true conditional mean of the state. What is possible to obtain is the best linear minimum variance estimator of the state. Under these assumptions one has a different threshold effect, once more quantified by the means and standard deviations of the multiplicative random white parameters, such that if this threshold is exceeded then the variance of the state estimation error increases without bound.

The final problem which was investigated involves the complete stochastic control of a linear dynamic system with both additive and multiplicative white noise parameters in the state dynamics, as well as in the measurement equation, and with respect to a quadratic performance index. Because of the infinite dimensional nature of the estimator for the true conditional mean of the state, a finite dimensional compensator approach was used. Essentially we have derived the mathematical characterization of the best linear contained finite dimensional estimator that transforms the noisy measurements into controls.

Even with these simplifications the problem of determining the best linear feedback dynamic compensator yields an extremely complex and highly coupled nonlinear two point-boundary-value problem, even in the case of scalar dynamics. The complex nature of the two point-boundary-value problem precludes any analytical insight to the problem, and thus the optimal stochastic control problem can only be solved through iterative numerical solution of the two point-boundary-value problem. Partial results have been obtained for the characterization of the threshold associated with this stochastic control problem, which marks the relationships between the total system and measurement uncertainty and the existence of an optimal finite dimensional linear compensator with constant parameters.

Full documentation of the above results will be found in the forthcoming doctoral thesis of Richard Ku which is scheduled for completion in June 1978.

2.2.2 On The Robustness of Constant Gain Extended Kalman Filters and Stochastic Regulators

The importance of the extended Kalman filter for state estimation, parameter estimation, and as an element of a stochastic regulator is well known. It is also well known that one of the great drawbacks of the use of the conventional extended Kalman filter in many applications results from its real time computational requirements. These are associated with the real time solution of the error covariance matrix calculation, which is needed to calculate in real time the numerical value of the filter gain matrix (which multiplies the residuals of the extended Kalman filter so as to correct the state estimates). Mr. Michael Safonov and Professor Michael Athans have examined in detail techniques by which one could implement nonlinear extended Kalman filters and stochastic regulators, with a precomputable constant residual filter gain. The use of a constant and precomputable residual gain has obvious implications with respect to the tremendous reduction of real time computation; on the other hand, one needs to be careful so as to prevent the divergence of the state estimates and guarantee the stability of the constant gain extended Kalman filter.

A set of very general sufficient conditions that guarantee the stability of the constant gain extended Kalman filter have been obtained. These sufficient conditions may provide the means for modelling approximations to be used in several nonlinear filtering problems for which the reduction of real time computations is essential.

In addition to the robustness results associated with the constant gain extended Kalman filter described above, we were able to obtain corresponding results for stochastic regulators. The intuitive explanation of the complicated mathematical stability sufficiency conditions for the stochastic regulator problem, can be described roughly as follows. If one has noisy measurements of the state variables, so that one is forced to use a Kalman filter (linear or nonlinear) for state reconstruction and possibly parameter estimation, then one must pay close attention to the overall robustness properties of the closed-loop system, and evaluate them by means of multivariable extensions of classical robustness criteria such as gain margins and phase margins. The results obtained indicate that one can approach the robustness properties of designs that employ feedback of noiseless measurements of all state variables, if real time identification and failure detection algorithms are used which communicate to the extended Kalman filter the best possible available model of the dynamic process, of its actuators, and of its sensors. On the other hand, the results obtained indicate that the overall design can be robust with constant filter residual gains and constant control gains. In other words, real time estimation of parameters, actuator and sensor changes and failures is very important, but real time reconfiguration of the filter and control gains is of secondary importance.

The above theoretical results lend credibility to the standard engineering practice of using ad-hoc rules for scheduling filter gains and control gains, and they also illustrate that complex approximations to the true dual control problem (with their resultant prohibitive requirements for real time solution of two point-boundary-value problems for the calculation of the both the filter gains and control gains) is not as important from an overall stability point of view. Further research in this general area is continuing, and only partial documentation of the above results is available (in a paper by Safanov and Athans in the Proceedings of the 1977 IEEE Conference on Decision and Control).

2.2.3 Singular Stochastic Control Problems and Dual Compensator Structures

Dynamic compensators for linear time-invariant plants subject to additive stationary plant and output noise disturbances are considered. Since very few practical systems are either purely linear or deterministic, the consideration of uncertainty is almost essential in control design. However, there are often situations where it is desirable to ignore "less significant" sources of uncertainty, e.g. when observation noise covariances are almost singular. Unfortunately, these situations can lead to severe numerical problems, e.g. in calculating Kalman filter gains. We seek a judicious way to ignore uncertainty in such singular stochastic control problems, which will neither lead to numerical difficulties, nor cause serious performance degradation.

It is now clear from the works of Davison [1] and others that this is intimately related to the ability to achieve static decoupling and disturbance rejection (i.e., reduction of output variance that is attributable to uncertain plant inputs). Along with stabilizabilty, these factors seem of primary importance in determining compensation order. However, the algorithmic and algebraic details remain to be worked out in a stochastic setting.

We are completing the results initiated in [2] in the light of recent research on this problem [3]. The optimum compensator can be interpreted as either: (1) an optimal minimal-order observer-based compensator for an optimally aggregated plant of dimension equal to that of the compensator plus the number of plant outputs or (2) an optimal minimal-order dual observer-based compensator for an optimally-aggregated plant of dimension equal to that of the compensator plus the number of plant inputs. The optimal aggregated models are related to the original plant model by a congruence transformation.

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2.3 RELIABLE CONTROL SYSTEM DESIGN

2.3.1 On Reliable Control System Designs With and Without Feedback Reconfigurations

Mr. J.D. Birdwell, Professor M. Athans and Dr. D.A. Castanon have continued their investigations in the area of stochastic control with special emphasis on developing a method of approach and theoretical framework which advances the state of the art in the design of reliable multivariable control systems, with special emphasis on actuator failures and necessary actuator redundancy levels.

The mathematical model consists of a linear time invariant discrete time dynamical system. Configuration changes in the system dynamics, (such as actuator failures, repairs, introduction of a back up actuator) are governed by a Markov chain that includes transition probabilities from one configuration state to another. The performance index is a standard quadratic cost functional, over an infinite time interval.

If the dynamic system contains either process white noise and/or noisy measurements of the state, then the stochastic optimal control problem reduces, in general, to a <u>dual</u> problem, and no analytical or efficient algorithmic solution is possible. Thus, the results are obtained under the assumption of full state variable measurements, and in the absence of additive process white noise.

Under the above assumptions, the optimal stochastic control solution can be obtained. The actual system configuration, i.e., failure condition, can be deduced with an one step delay. The calculation of the optimal control law requires the solution of a set of highly coupled Riccati-like matrix difference equations; if these converge (as the terminal time goes to infinity) one has a reliable design with switching feedback gains, and, if they diverge, the design is unreliable and the system cannot be stabilized unless more reliable actuators or more redundant actuators are employed. For the reliable designs, the feedback system requires a switching gain solution, that is, whenever a system change is detected, the feedback gains must be reconfigured. On the other hand, the necessary reconfiguration gains can be precomputed, from the off-line solutions of the Riccati-like matrix difference equations.

Through the use of the matrix discrete minimum principle, a suboptimal solution can also be obtained. In this approach, one wishes to avoid the reconfiguration of the feedback system and one wishes to know whether or not it is possible to stabilize the system with a constant feedback gain, which does not change even if the system changes. Once more this can be deduced from another set of coupled Riccati-like matrix difference equations. If they diverge as the terminal time goes to infinity, then a constant gain implementation is unreliable, because it cannot stabilize the system. If, on the other hand, there exists an asymptotic solution to this set of Riccati-like equations then a reliable control system without feedback reconfiguration can be obtained. The implementation requires constant gain state variable feedback, and the feedback gains can be calculated off-line.

In summary, these results can be used for off-line studies relating the open loop dynamics, required performance, actuator mean time to failure, and functional or identical actuator redundancy, with and without feedback gain reconfiguration strategies.

The above results have been partially documented in a paper in June 1977 IEEE Conference on Decision and Control. Full documentation will be contained in the doctoral thesis by J.D. Birdwell, scheduled for completion in June 1978.

2.3.2 Fault-Tolerant Optimal Control Systems

Professor A.S. Willsky and Mr. H. Chizeck have undertaken the problem of trying to determine controllers which optimize performance prior to failure but are content to operate in a degraded mode subsequent to failure-- i.e., optimal self-reorganizing controllers, rather than robust controllers, which sacrifice some performance prior to failure to guarantee adequate performance if a failure occurs. Clearly the former system requires an excellent fault detection system, while the latter may lead to significant performance loss if failures are unlikely to occur.

Since our criteria of performance depends upon the system mode, we are led to consider a "split-cost" formulation. In the simplest case, in which there are two modes, denoted by $i = 1, 2$

$$\dot{x}(t) = Ax(t) + B_i u(t) + W_i(t) \tag{1}$$

where the system starts in mode one and may switch to mode two at unknown failure time T. Here x is the state, u the control and w white noise. The basic optimal control problem is to solve for the optimal control u(t) assuming perfect knowledge of x(t) and the mode i(t), where the cost criteria is

$$J = E \int_0^T [x'(t)\, Q_1\, x(t) + u'(t) R_1\, u(t)]\, dt + \int_T^{t_f} [x'(t) Q_2 x(t) + u'(t) R_2 u(t)]\, dt \tag{2}$$

This problem has been solved, as have extensions to more complex problems, such as the inclusion of an arbitrary but finite set of modes. In addition, we have begun to attack the problem of the design of a useful maintenance policy, where we model the decision to perform maintenance as a switch of the system to a new model (perhaps restored to the original operating state) at some fixed maintenance cost. A solution to a simple form of this problem has been obtained, and we are continuing to analyze the nature of this formulation and its solution.

In addition to continuing our studies of the problems mentioned above, we are adding complexity to the model by including measurement noise. No difficulties should be encountered if we have noisy linear observations of x and perfect knowledge of the mode. If knowledge of the mode is dropped, the problem becomes a dual control problem. However, our earlier work should allow us to study this problem at some depth. Specifically, the control law for the problem (1)-(2) switches at failure times. If we don't observe the mode directly, this switch basically must be replaced by a failure detection system. We hope to analyze the performance of this detection system not by itself but as it effects the performance of the overall closed-loop system.

2.4 Stochastic Control Laws Implemented by Finite-State Sequential Machines

The effects of plant and measurement noise on digital controllers synthesized with finite-state sequential machines are qualitatively different than corresponding effects for continuous-time analog controllers or discrete-time controllers performing real-number operations. The latter effects have been extensively analyzed in the literature [1]; but the former effects have been primarily studied as quantization noise when a digital controller is designed to mimic a discrete-time controller performing real-number operations [2]. The relative limitations and strengths of finite-state sequential machines as controllers in the presence of uncertainty are probably better understood by practitioners than control theoreticians today.

We are developing a mathematical formulation that will permit the assessment of the performance of asynchronous finite-state sequential machines used as stochastic controllers for continuous physical systems. In the derivation of stochastic control laws an important first step is the ability to predict the closed-loop system response for a known input and initial condition, and a known control law. Then by assigning a measure of probability to each possible input and initial condition, the expected performance of the controller can be computed; one can then further proceed to design questions such as finding optimum control law parameters. It is in the first step--an essentially deterministic problem--that we have met with some success.

In contrast to the usual discrete-time dynamic system, whose time-set is a subset of the integers and whose state-space is a real vector space, an asynchronous finite-state sequential machine evolves on an integer time-set but with a state-speace that is the product of a finite set and a set of real numbers which represent transition times. Thus, finding the next "state" involves finding the next machine "state" (element of a finite set) and the next transition time(s), a (set of) real number(s). Details are spelled out in [3].

The validity of this idea has been established by examining several examples. These involve a logic network with incomensurate feedback delays, a stablizing relay-controller for an unstable first-order system, and optimal linear controllers based on integer machines (see [4]).

We have proposed to continue research on this class of systems. There is yet a need to determine the structure of a general class of encoders mapping real-valued time-functions (plant outputs) into sequences in an appropriate product space. We also need to determine when the switching-time transition-function can be realized by an automaton. The growing literature on switching theory and asynchronous automata (much of which is in Russian) may provide some answers to these questions.

In a stochastic setting, it appears that the theory of unknown-but-bounded processes [5] will be most useful in analyzing the behavior of continuous plants controlled by computers. One promising feature of such quantized controllers is insensitivity to noise which is smaller than the smallest quantization levels; thus while a large quantization step-size may penalize controller accuracy, it could also lead to noise immunity. A quantitative assessment of such tradeoffs is clearly desirable.

To date, our most significant findings are considered to be:

(1) A realization for hybrid feedback systems (Johnson, 1978) which may lead to new methods of engineering analysis and simulation for asynchronous processes.

(2) Demonstration of local stabilizability of an unstable first-order system by the simplest type of synchronous finite-state controller (Wimpey, to appear).

(3) Definition of a broad class of functions termed "normal" functions for which asynchronous memoryless coding is a continuous operation (viz. a small change in the input function produces a small change in the transition times). (Jones, to appear).

(4) A strictly stable linear system defined on integers must have a nilpotent transition matrix; hence, useful approximations of continuous linear dynamic systems require large-dimension integer systems. (Davis, 1977).

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1. REPORT NUMBER AFOSR-TR- 78-0910	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) STOCHASTIC AND ADAPTIVE SYSTEMS		5. TYPE OF REPORT & PERIOD COVERED Interim
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Michael Athans and Sanjoy K. Mitter		8. CONTRACT OR GRANT NUMBER(s) AFOSR 77-3281
9. PERFORMING ORGANIZATION NAME AND ADDRESS Massachusetts Institute of Technology Electronic Systems Laboratory Cambridge, Massachusetts 02139		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 2304/A1 61102F
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Office of Scientific Research/NM Bolling AFB, Washington, DC 20332		12. REPORT DATE 1978
		13. NUMBER OF PAGES 19
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Non-linear filtering, estimation of random fields, stochastic control, reliable control system design and implementation of control laws.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This research is concerned with various aspects of stochastic and adaptive systems. Topics covered include: non-linear filtering, estimation of random fields, stochastic control, reliable control system design and implementation of control laws.

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